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THE HYDROGEOMORPHOLOGY OF THE CARRAN ENCLOSED DEPRESSION, CO. CLARE, IRELAND

by

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ABSTRACT

The plateau surface of the central Burren is pitted with numerous enclosed depressions with internal drainage, of which that centred on Carran is the largest. The water sinking at the southern end of the depression had previously been traced to springs in the valley of the River Fergus to the south. The discovery in 2009, of a major, vertical cave (Poll Gonzo) near the northwestern extremity of the enclosed basin, stimulated new research in the area which is described in this paper. Positive water tracings from Poll Gonzo to submarine springs in Galway Bay and from the Castletown sink to the River Fergus valley springs show that the Carran depression lies on the divide for north and south draining groundwaters. The Carran enclosed depression is a complex karstic landform composed of seven sub-basins. Based on its morphology and hydrology it is suggested that the enclosed depression can be regarded as a small polje, an uncommon karst landform in temperate climates.

INTRODUCTION

This paper is concerned with detailing recent research which has clarified the geomorphology and the internal and external drainage of the Carran enclosed depression. The dominant landform of the central Burren is an inclined plateau extending from the scarp which overlooks Galway Bay in the north at c.300 m O.D., to the valley of the River Fergus in the south at c.30 m O.D. The gentle topographic slope approximates to the overall dip of the Carboniferous limestone strata (0-5^{o} to the south-southwest). Gorge-like segments of dry valleys and numerous dolines characterise this part of the central Burren but the dominant landforms are the compound enclosed basins of Kilcorney-Meggagh (floor area c.7 km^2) and Carran (floor area c.8 km^2) shown in Figure 1. Mullan (1998) described the geomorphology of the Kilcorney depression and this paper is concerned only with the more easterly landform centred on Carran (sometimes spelt Carron).

There are few publications which present original research into aspects of the Carran enclosed depression. The first description of the hydrogeomorphology of the area was by Sweeting (1953) who reported that “water was believed to flow south to the River Fergus”. Tratman (1969) described a water tracing experiment linking the swallow hole in the south of the depression with springs in the valley of the River Fergus. Drew (1988) presented the results of water tracings to springs in the same valley including attempts from the Carran area.

Until recently the only major cave known that was directly associated with the Carran enclosed depression was the Fergus River Cave located on the northern flank of the upper River Fergus valley. Here, more than 3 km of periodically active stream passages (a resurgence) have been explored, mainly by University of Bristol Speleological Society cavers, summarised in Mullan (2019). A direct link between this cave and the stream sink in the Carran depression has been assumed, although the quantity of water sinking in Carran is only a small fraction (c.10%) of the groundwater discharge in to the upper course of the River Fergus between the spring at Poulnaboe and those at Elmvale some 2 km down-valley (Figure 2). In

2009 a significant new cave, Poll Gonzo (Bunce, 2010), was discovered within the Carran enclosed depression prompting this research.

Although this paper is primarily concerned with the Carran enclosed depression the fact that water sinking underground in the depression resurges in the valley of the River Fergus to the south and in Galway Bay to the north means that some consideration is also given to this wider area.

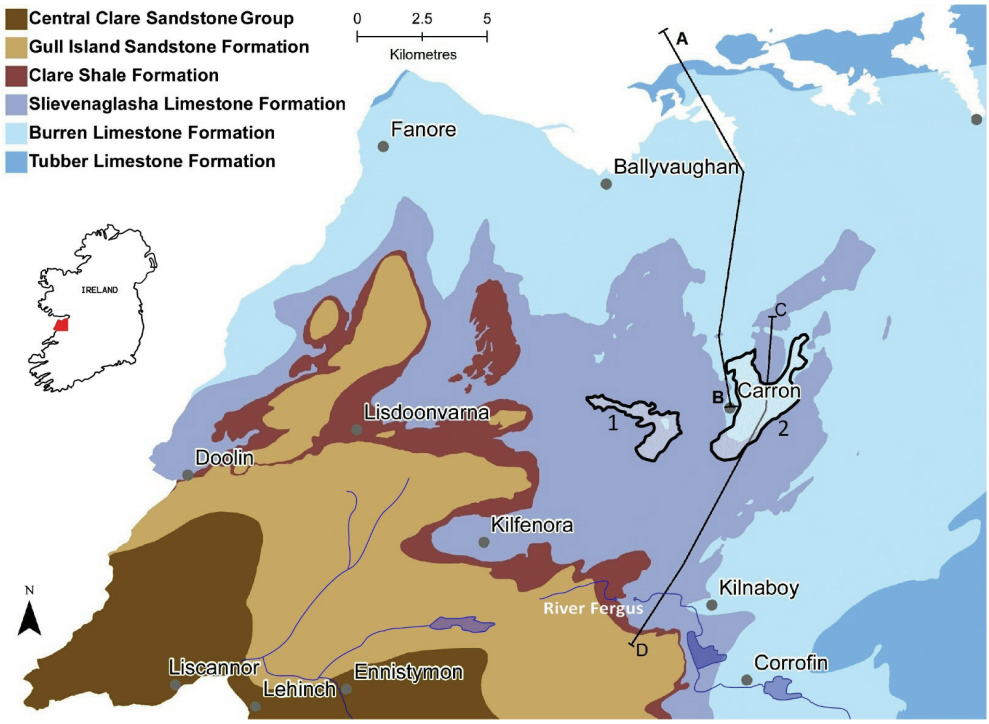

Figure 1. *Outline geological map of the Burren showing the location of the enclosed depressions at Kilcorney-Meggagh (1) and Carran (2). Also showing the location of cross sections A-B and C-D shown in Figure 10.*

Map modified from an original by the Burren and Cliffs of Moher Geopark.

MORPHOLOGY OF THE CARRAN ENCLOSED DEPRESSION

We have defined the boundary of the depression as the 140 m contour. This contour is almost completely closed except at the southern end of the depression where a narrow col with a low point of 135 m, leads to the Glencurran valley. The 140 m contour outlines a Y- shape with a total area of 8 km² (Figure 3). The Carran depression is incised some 60 m into the general Burren plateau surface and contains seven smaller sub-basins nested within the main feature, these are shown on Figure 3, and are described below. The main dimensions of each sub-basin are listed in Table 1. Table 2 contains details of the individual karst features within each sub-basin.

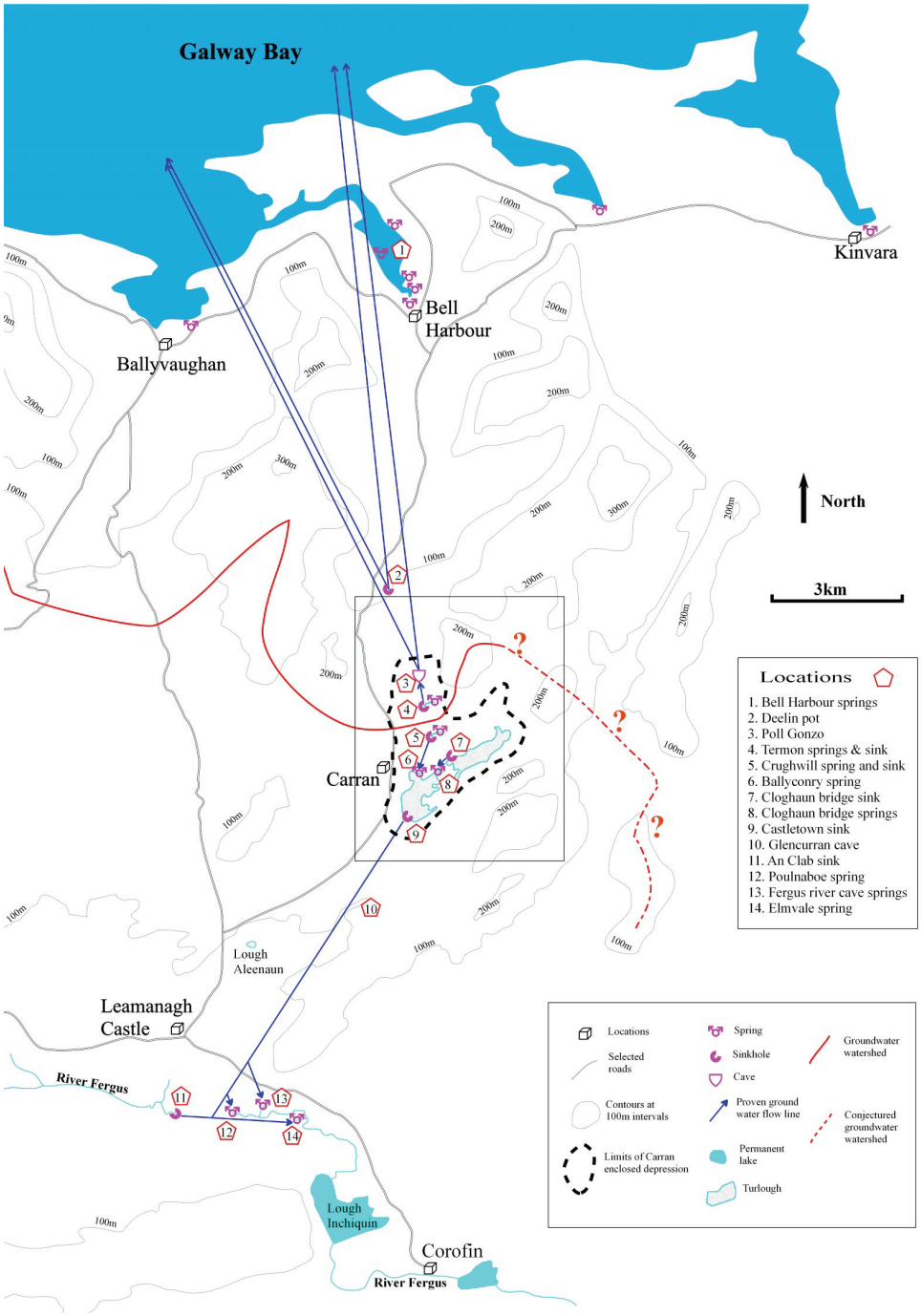

Figure 2. *Proven internal and external water traces in the Carran enclosed depression. Box indicates the area shown in Figure 3.*

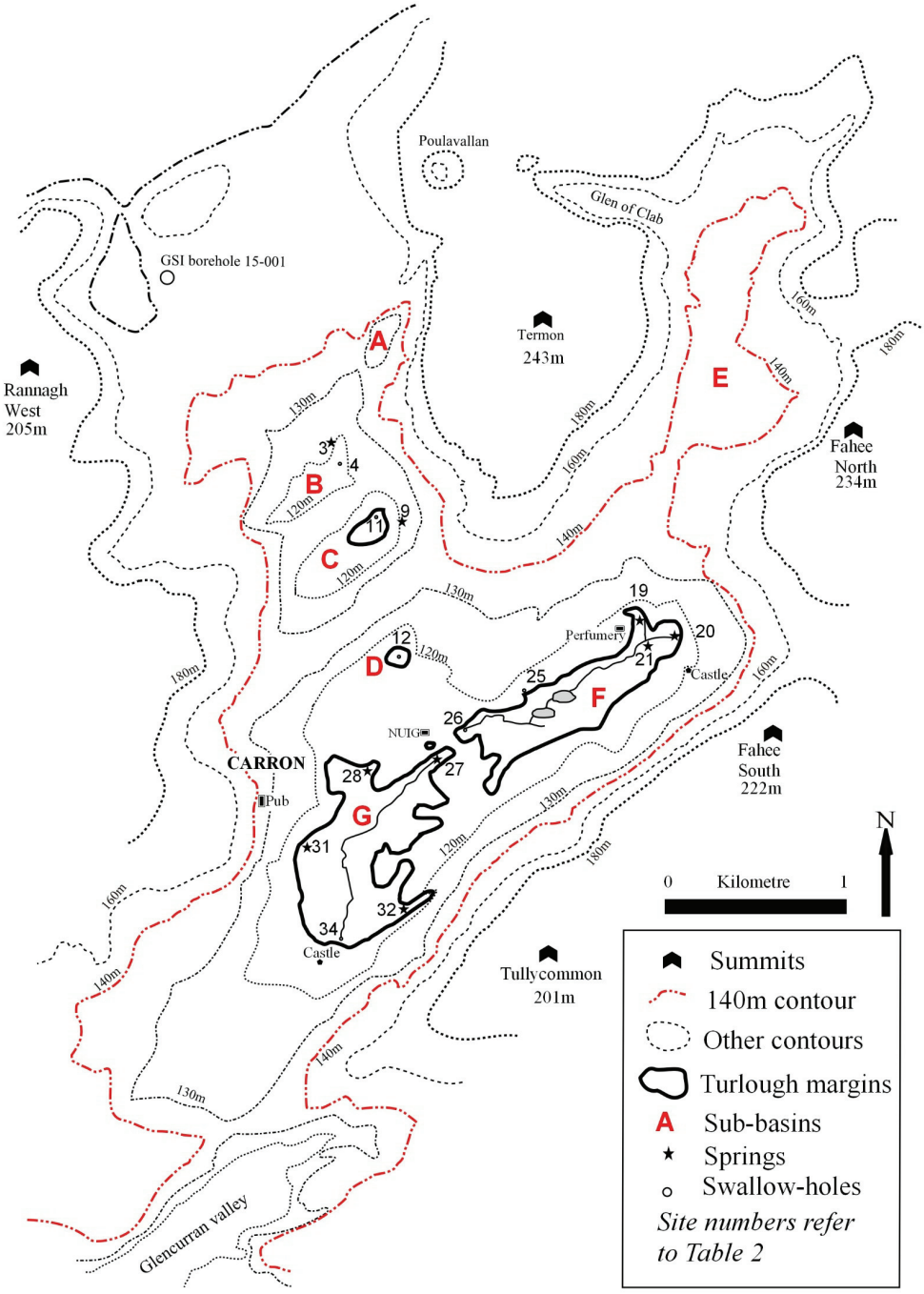

Figure 3. *The Carran enclosed depression showing sub-basins A-G and selected karst features.*

Table 1. *Sub-basins in the Carran closed depression.*

	A	B	C	D	E	F	G
Name/ Townland	Poll flahatha	Rannagh/ Gonzo	Termon	Crughwill	Poul aloughan	Upper turlough	Lower turlough
Area km^2	0.11	0.21	0.12	0.03	0.3	0.3	0.4
Lowest point a.s.l.	130 m	114 m	114 m	112 m	120 m	111 m	110 m

The north-western limb of the depression, leading towards Rannagh, contains 4 sub-basins: A, B, C and D. Further north along the same line, but outside the boundary of the enclosed depression, is Poulavallan a large doline with a diameter of 300 m and depth of 30 m.

Basin A has exposed bedrock in both the floor and sides. There are no active karst features but there is one short inactive cave. Basin A is separated from basin B by a ridge of bedrock c.10 m high.

Basin B contains extensive glacial deposits on the floor, however, bedrock is visible near Poll Gonzo. Three small springs are located on the west side of the basin but all sink within a few metres. The sides of the northern half of the basin are bedrock while the southern margin is a ridge of till about 10 m in height separating this basin from basin C.

Basin C has some exposed bedrock on the floor but there is soil cover in places. A number of springs are located on the east side of this basin and some have been capped by the local authority for water supply. At the lowest point there is a narrow rift in the bedrock which acts as a sinkhole, however following heavy rain much of the basin floor can become submerged. This basin is separated from basin D by a ridge of till c.15 m in height.

Basin D is a shallow depression with some bedrock exposed where the water from three springs combines and sinks within 10 m. Basin D is separated from basins G and F to the south and southeast by an area of bedrock 600 m wide but which is only a few metres high.

Basin E occupies the northeastern limb of the depression and contains extensive glacial deposits on the floor; although the sides are mostly bedrock. A dry valley enters the basin from the south. Springs on the northern edge of the basin become active in wet weather, the water sinking in a grassy area in the floor of the basin. Basin E is separated from the Glen of Clab to the west by a ridge of till and is separated from basin F to the south by a ridge of limestone at least 20 m in height.

The third limb of the Carran depression is the most southerly and is oriented northeast-southwest. It contains the two largest sub-basins - basins F and G (Figure 4).

Basin F has an extensive flat floor (1.4 km long and 0.33 km wide) with a permanent stream which is fed from several springs at the northeastern end and sinks at the southwestern end of the basin. One cave, Poll Fionn, is known in this basin; it is located on the northwestern edge just above the level of the basin floor. Glacial deposits occur on the margins of the basin, some forming drumlinoid mounds with the same NE – SW orientation as the basin. Similarly orientated glacial striations can also be found on bedrock exposed on the basin floor where the till has been eroded.

Basin G is separated from basin F by a 350 m wide low ridge (c.3 m high) of bedrock largely exposed as limestone pavement. On the northwestern side of the ridge a shallow channel connects the sub-basins; this channel may be wholly or partly man-made.

Table 2. *Karst features of the Carran depression*

Basin	Site name	Site No.	ITM	Alt	Description	Traced
A	Poll Bru	1	528470 201270	128 m	10 m long inactive cave	
B	Spring/sink (N)	2	528310 701107	128 m	Small permanent spring and sink system	
	Spring/sink (S)	3	528212 700880	124 m		To Poll Gonzo North
	Poll Gonzo	4	528280 700704	114 m	90 m deep active cave	To Galway Bay
	Spring	5	527900 700350	125 m	Small permanent spring on west side of basin	
	Sinkhole	6	527960 700425	117 m	Choked	
	Sinkhole	7	528278 700627	113 m	Choked	To Poll Gonzo upper inlet
	Sinkhole	8	528041 700438	114 m	Choked	
C	Termon upper springs	9	528646 700246	121 m	2 permanent springs (1 capped) on the same bedding plane	
	Termon lower springs	10	528476 700185	114 m	Almost on the floor of the turlough	
	Termon lower sink	11	528398 700279	114 m	Narrow rift in bedrock	To Poll Gonzo main inlet
D	Crughwill spring/sink	12	528645 699590	112 m	3 springs combine and sink within 10m (wayboard)	To Ballyconry springs
E	Termon East cave	13	530148 701750	150 m	Minor resurgence with 10 m cave (wayboard)	
	Coskeam cave	14	530952 701973	159 m	Short inactive cave	
	Coskeam sink	15	530900 701220	145 m	Marshy area	
	Flood springs	16	531190 702950	190 m	Series of springs only active in flood	
	Flood sink	17	531017 702694	145 m	Diffuse grassy choked sink, active in flood	
	Fahee north cave	18	530375 700298	152 m	Short dry cave	

Basin	Site name	Site No.	ITM	Alt	Description	Traced
F	Northern springs	19	529960 699870	119 m	Number of wet weather springs from bedding horizons	
	Castle springs	20	530175 699750	116 m	2 springs from bedding horizons on turlough margin	
	Pumphouse springs	21	529760 699515	113 m	2m deep hole in bedrock in middle of turlough provides constant water supply c.3,000 litres per day.	
	Fahee North spring 1	22	530365 699390	136 m	2 springs near base of cliff, water sinks before reaching turlough. Water also emerges on cliff face	
	Fahee North spring 2	23	530500 699445	152 m	Spring from low bedrock parting supplies cattle trough before sinking	
	Glen Cairn Farm Spring (?)	24	529620 699265	113 m	Within turlough margin, not visible but shown on 6 inch map. Occasional spring in front of farmhouse	
	Poll Fionn	25	529288 699404	111 m	C 70 m long low muddy cave	
	Cloghaun bridge sink	26	529025 699270	111 m	Water sinks at several points along bedrock margin of upper turlough	To Cloghaun bridge spring in basin G, 250 m
G	Cloghaun bridge springs	27	528810 699035	110 m	Several springs on both sides of channel leading SW from Cloghaun bridge	From Cloghaun bridge sink 250 m
	Ballyconry Springs	28	528490 699030	110 m	Diffuse spring on bedrock/turlough margin. SE spring can act as sinkhole	From Crughwill sink 600 m
	Ballyconry flood spring	29	528185 699020	118 m	Flood spring only, bedrock/drift boundary	

Basin	Site name	Site No.	ITM	Alt	Description	Traced
G	McGann's spring	30	528425 697895	123 m	Walled spring in field on bedrock / drift boundary. Water sinks after 50 m	
	Hehir's springs	31	528075 698560	111 m	3 springs on bedrock/turlough margin	
	Fianna Cait (Cat's Well)	32	528727 698232	118 m	Small spring in gully (wayboard)	
	Poll Uaigneach	33	528900 698080	140 m	Short dry cave on east side of depression	
	Castletown river sink	34	528302 698041	110 m	Diffuse muddy sink under low cliff	To Fergus river risings

Basin G is the most southerly and the lowest basin in the depression. It also has an extensive flat floor (1.13 km long and 0.6 km wide) with a permanent stream crossing the basin from springs on the northwestern side to a sink below a low cliff at the southern end. Crabtree (1982) investigated the depth and nature of the sediment fill within this basin and described:

> *"generally shallow (less than 2 m) peat and clay infill but at one point 4 m of sediment was found with clays, lake muds and peats."*

However, no locations are given for the sites that were augered.

Two other features in basin G are:

a. Poulmoneen, a shallow depression 100 m by 30 m at the northern end of the basin. It contains a turlough and is separated from the main area of basin by a drumlinoid feature c.100m wide.

b. A pronounced gully on the southeastern margin which is aligned parallel to basin G and opens onto the main basin at its southwestern end.

As noted earlier, the southern limb of the enclosed depression is separated from the Glencurran valley only by a narrow col. Glencurran is a pronounced gorge-like feature that originates on the south western flank of Slievenaglasha Hill and runs south-southwest for c. 4 km before terminating in the vicinity of Lough Aleenaun turlough. The significant Glencurran Cave originates on the southern side of the valley. It is unclear whether the Glencurran valley and cave are genetically and functionally related to the Carran depression.

GEOLOGICAL INFLUENCES ON THE LANDSCAPE AND CAVES

Detailed geological mapping and borehole logging by Geological Survey Ireland along with the recent exploration of new caves in the area have led to a greater understanding of the local geology. Gallagher *et al* (2006) gives a detailed description of the full limestone sequence.

Almost the entire floor of the depression is formed of limestone from the Aillwee Member (Burren Formation). This member is characterised by massive limestone beds separated by thin clay/shale beds known as wayboards (Walkden, 1974). Wayboard exposures can be seen in sub-basins B, D, E and G (see Table 2 for locations); the floor of basins B, C and D probably are all developed on the same wayboard horizon. Above the 140 m defining contour,the break of slope at the margin of the depression corresponds approximately to the boundary between the Burren Formation and the succeeding Slievenaglasha Formation.

Figure 4. *The Carran enclosed depression: View looking west in winter (top) and summer (lower) showing sub-basins F (right) and G (left).*

A Geological Survey Ireland borehole (15-001) at Rannagh (ITM 527450 701448, 2.5 km north of Carran) shows a sequence of 7 wayboards the lowest being 2.4 m thick. Figure 5 shows the correlation between the borehole log and the profile of Poll Gonzo and indicates the significant influence of the wayboards as inception horizons in the development of the cave. The main stream enters from a southerly direction along a passage with a well exposed wayboard 0.1 m to 0.25 m in thickness (Figure 6). Another horizontal passage at a higher level also corresponds with a wayboard, but which appears locally in the cave as a 10cm thick calcite layer. Minor horizontal developments at lower levels also correspond with wayboard horizons. The sump at the lowest point in the cave (28 m OD) correlates with the base of the Aillwee Member; the limestone unit below this is the Maumcaha Member described as "massive to poorly bedded" with weak jointing which may explain the lack of cave development below this level.

North-south orientated calcite veins are ubiquitous throughout the Burren (Gillespie *et al* 2001), but similarly orientated veins in the Carran area also include quartz and sulphide mineralisation (Walsh *et al*. in review). Geological Survey Ireland mapping shows that an array of these siliceous veins occur in this area (Figure 7). Some were the focus of small-scale mining activity in the nineteenth century; others can be seen on the surface as upstanding features <1m in height and width (Figure 8). These mineralised veins are generally orientated either north-south or at 010 - 015^0 and have thicknesses up to c.50 cm. The horizontal extent of individual

veins is usually <200 m but they often have an en-echelon pattern (Walsh *et al*. in review). Siliceous veins are clearly exposed in Poll Gonzo and appear to be the focus for water flow through the wayboards that has allowed the cave to develop to its significant depth. In Poll Gonzo a vein system can be seen through the full 90 m depth of the cave, in one part of the cave 3 separate veins can be seen within a 2 m horizontal range (Figure 9). Five kilometers north of Poll Gonzo a similar vein system can be seen on Turlough Hill extending vertically from the valley floor (c.70 m) to the summit plateau (c.280 m) showing the vertical persistence of these features. Sub-basins A and B, the large doline at Poulavallan and the Carran mine adits are all aligned on the same vein system as Poll Gonzo.

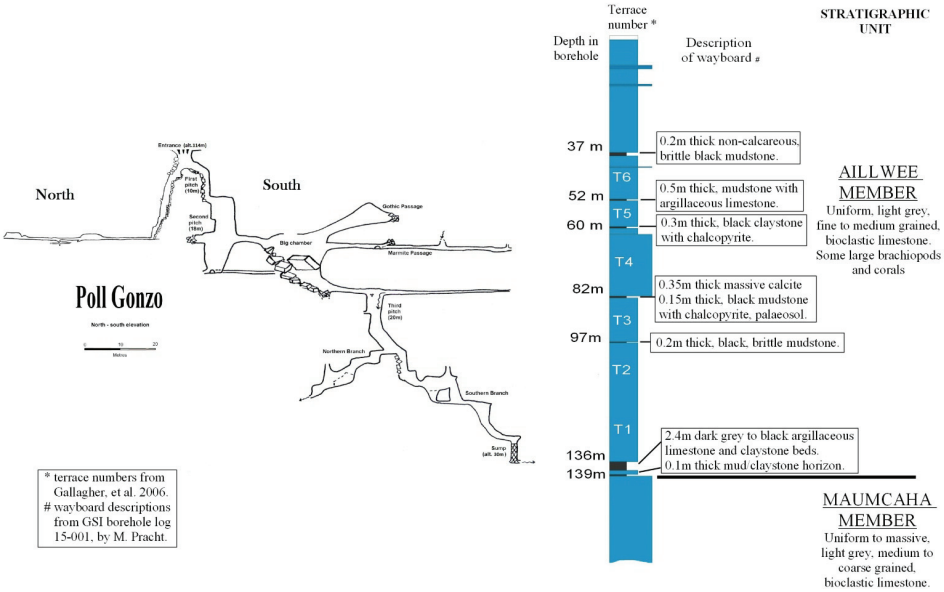

Figure 5. *Profile of Poll Gonzo correlated with wayboard horizons from GSI borehole 15-001.*

To the north of the Carran area the limestones have a uniform southward dip of c.2° (Figure 10: cross section A-B); however, south of the northern limits of basin F the beds are more folded (Figure 10 cross section C-D). Geological Survey Ireland mapping shows a series of northeast-southwest orientated folds plunging gently to the southwest but with strongly asymmetric forms (Figure 7); this fold system is clearly exposed at Mullagh More, 6 km south-east of Carran. Locally the southward dipping limbs of the folds approach angles < c.30° and have been described as monoclines (Walsh *et al*. in review). The monoclines have axes varying from a few hundred metres to c.1 km in length. Their asymmetric nature has been attributed to the inversion of northward-dipping normal faults in the underlying lower Carboniferous sequence (Walsh *et al*. in review). The fold axes swing from a generally northeast-southwest trend in the eastern Burren to a roughly east-west orientation in the west (Walsh *et al*. in review).

At the northern end of basin F dips of 6° and 7° are recorded; while at the southern end of basin G near the Castletown sink dips reach 30° over a small area and may be

responsible for the pronounced gully found here. A large monocline is visible on Slievenaglasha (south-east of the Carron depression) with dips of c.30° over a length of c.1 km. The Glencurran valley is aligned along another monocline for a length of c.1 km with dips of >20° and the cross-sectional form of this asymmetric valley closely reflects the form of the monocline. The River Fergus valley also appears to be aligned on another fold with dips of 13° recorded between Leamaneh Castle and Parknabinnia, although this area is outside that covered by detailed Geological Survey Ireland mapping.

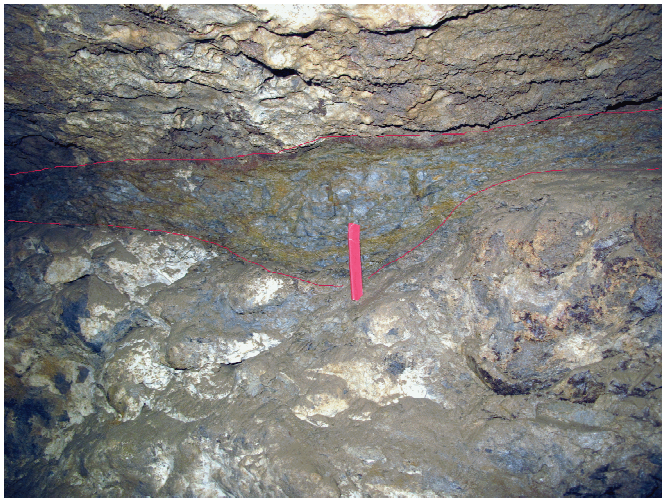

Figure 6. *Wayboard exposure in Poll Gonzo. Verical bar is 10 cm.*

On Slievenaglasha and also at Parknabinnia, the limestone exposed at the surface is the Lissylisheen Member - the uppermost unit of the limestone (Figure 7) which has a total thickness of only 1- 2 m (Gallagher *et al*, 2006). Its presence in these locations indicates that very little erosion of the limestone surface has occurred, at least in some places, following removal of the overlying Clare shales; so the shape of the landscape closely reflects the geological structure. Previous surface drainage patterns on the shales may have been influenced by these fold patterns

HYDROLOGICAL INVESTIGATIONS

Following Sweeting's (1953) description of the depression, various attempts were made to ascertain the destination of water sinking at the Castletown sink. A summary of these water tracings is presented by Drew (1988).

The discovery of a large stream inside the Poll Gonzo cave system led to a re-examination of the internal hydrology of the Carran depression. A number of previously unknown semi-permanent springs and sinkholes were located (listed in Table 2) making apparent the need for more water tracing. Between 2011 and 2018 a series of tracings were carried out to ascertain the internal and external drainage of the various sub-basins within the larger enclosed depression; these are summarised in Table 3 and depicted graphically in Figure 2. Other information was obtained through hydrometric data collection in the two main turloughs by Geological Survey Ireland and Trinity College Dublin, and from local residents.

The Carran depression has wholly karstic drainage, being fed by numerous internal springs and drained by significantly fewer swallow holes. In the northern limb of the depression present day surface drainage is very limited, although Poll Gonzo is clearly a major site of point recharge, albeit with limited expression at the surface. The upper levels of the cave are inactive but at a depth of 40 m below the entrance a stream enters the southern arm of the cave with a

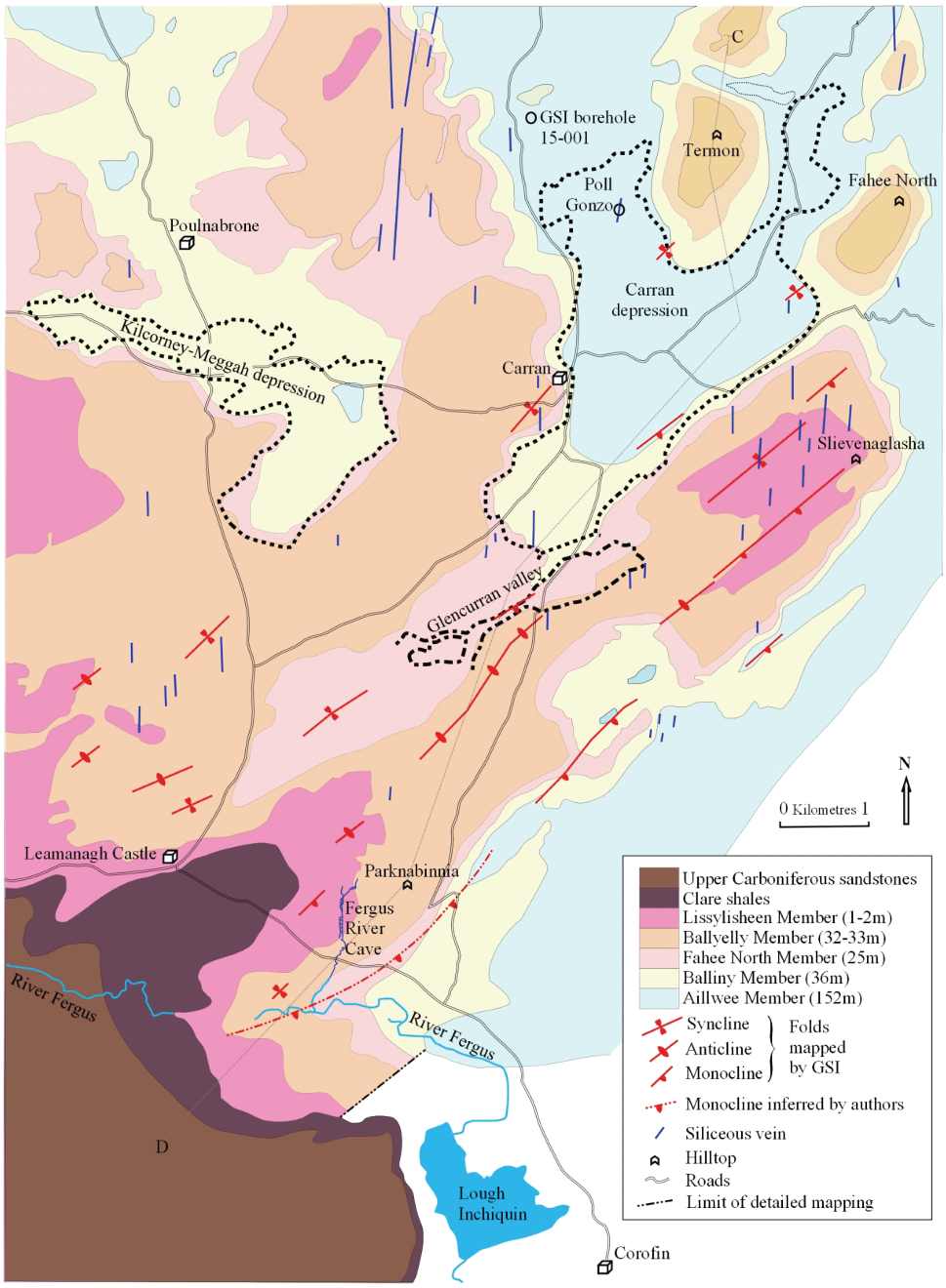

Figure 7. *Geology of the Carran area showing folds and veins based on Geological Survey Ireland field mapping and structures inferred by the authors.*

flow estimated to be <100 ls^{-1}. Water has been traced to this point from one of the sinks in basin B and from Termon lower sink in basin C although these do not appear to account for all the inflow. Other springs in basin B have been traced to a separate stream in Poll Gonzo North which probably combines with the main cave stream further north and at a lower level. In 2018 the water from the sump in Poll Gonzo was traced to offshore springs in Galway Bay located between Ballyvaughan and Aughinish at distances of 500-1500 m offshore and at depths of <5m. (Schuler *et al*, 2018, 2019).

Basin E contains a significant flood sink, and while no tracing has been attempted here, flood water probably flows north to Galway Bay.

The southern arm of the depression has the best developed surface drainage system. Water enters basin F from springs on the margins of its northern end, and also from the Pumphouse spring which is located centrally within the turlough in this area and supplies >3,000 litres per day to the Burren Perfumery. The Pumphouse spring has never been known not to flow, even during the very dry summer of 2018 (R. Doyle, *pers comm*.), although the source of this water is unknown. The combined flow sinks at the south-west end of basin F at Cloghan bridge sink where discharge has been estimated at c.30 ls^{-1} during low flow conditions. During high water conditions much of the floor of this basin is submerged, a maximum water depth of 0.6 m was recorded at the sink in the winter of 2014-15.

Figure 8. *Silica vein outcrop, Eanty Beg Townland.*

The water from basin F resurges at Cloghaun bridge springs 250 m to the south-west in basin G, where it is joined by water from basin D resurging at Ballyconry spring and water entering from the west at Hehir's spring. The combined flow becomes the Castletown River which flows across the basin to the Castletown River sink - the lowest point in the entire depression at 110 m OD. Discharge at this point has been estimated at c.50 ls^{-1} during low flow conditions. During high water conditions the floor of this basin is totally submerged, a maximum water depth of 2.2 m was recorded at the sink in the winter of 2014-15. This water was traced to the River Fergus valley in 2015, first resurging at Poulnaboe, then 20 hours later at Elmvale (details are given in Table 3).

Table 3. *Summary of water traces in the Carran area 2011-2018. (positive traces shaded).*

Tracer input location	Traced by	Date	Tracer & amount	Sites monitored	Results	Flow rates
Termon sink	CCC	6/2011	OB 5 l	Poll Gonzo (main streamway)	+ve (on cotton wool	N/A
Cloghaun bridge sink	CCC	12/2014	OB	Poll Gonzo & 3 springs in Carran lower turlough	All -ve	N/A
Cloghaun bridge sink	DD/ CCC	6/2015	OB 8 l	Poll Gonzo, 5 x Fergus springs, 7 intertidal/ submarine springs, 4 boreholes in Turlough valley	All -ve	N/A
Sink 150 m NNW of Poll Gonzo	CB	3/2017	Fl 50 gm	Poll Gonzo north stream	+ve (on charcoal)	N/A
Poll Gonzo	NUIG	2,011	Fl 5 kg	4 intertidal /submarine springs in Bellharbour Bay and Corranroo	All -ve	N/A
Poll Gonzo	DD/ CCC	6/2015	Rh 20 l	5 x Fergus springs 7 intertidal /submarine springs 4 boreholes in Turlough valley	All -ve	N/A
Poll Gonzo	TCD	7/2017	RH 2 l	GSI borehole at Turlough and oyster spring (Bell Harbour)	-ve	N/A

Tracer input location	Traced by	Date	Tracer & amount	Sites monitored	Results	Flow rates
Poll Gonzo	TCD	14/4//2018	Fl 25 kg + 200 l of Keruing wood chips	Fergus river, Galway bay springs and offshore.	+ve to offshore springs in Galway Bay	N/A
2 sinks ENE of Deelin Pot	CB	3/2017	Fl 50 gm	Deelin Pot inlet	Both +ve (on charcoal)	<50 m/hr
Deelin beg Pot	TCD	14/4/2018	Rh 25 kg	Fergus river, Galway bay springs and offshore.	+ve offshore Galway Bay	N/A
Cloghaun bridge sink	DD/ CCC	4/2016	Fl 5 l	3 springs in Carran lower turlough	+ve at Cloghaun bridge spring	N/A
Crughwill sink	CB	4/2018	Fl 500g	Poll Gonzo, Termon lower, Cloghaun bridge springs, Ballyconry spring, Hehir's spring.	+ve at Ballconry	c. 50 m/hr
Castletown sink	DD/ CCC	6/2015	Fl 20 l	Poll Gonzo, 5 x Fergus springs, 7 intertidal /submarine springs, 4 boreholes in Turlough valley	+ve at: 1st Poulna-boe (7,340m, 120hrs), 2nd Elmvale (6,700m, 140hrs) 3rd Fergus springs (180hrs)	First trace at Poulnaboe after 120 hrs, persisted for >7 days, peak at 150 hours. c.60m/hr First trace at Elmvale after 140 hrs, persisted for 16 days , peak at c.200 hours c.45m/hr
An Clab	DD/CB	6/2014	Fl 5l	Poulnaboe (no flow) Buntober Cross bridge Elmvale	+ve at Elmvale	50-75 m/hr.

Figure 9. *Three silica veins exposed in Poll Gonzo.*

SUMMARY AND CONCLUSIONS

1. The Carran enclosed depression is a complex landform comprising several smaller depressions nested within a larger feature and with each sub-basin having its own internal drainage. In some instances the internal sub-basins are separated by bedrock ridges, in others by glacial deposits. The floor of the main depression is underlain by the Aillwee Member of the Burren Formation while the bounding slopes are developed largely in the Balliny Member of the Slievenaglasha Formation.

The landform may have been initiated on the non-calcareous (Namurian) strata which formerly overlay the limestone in this area, and then been superimposed onto the limestone, as is taking place at present at locations on the western Burren, these ideas have previously been discussed by Drew (1988) and Simms (2003). Vertical development of the depression may have been inhibited when the base of the depression reached the level of the relatively impermeable wayboards, whereupon lateral solution became dominant.

2. Numerous small springs and seepages drain into the main depression, in particular to the north-western and north-eastern limbs. Surface drainage converges in the southern part of the Carran depression and eventually sinks at Castletown, the lowest point of the enclosed depression. This water flows initially to Poulnaboe and the springs below Fergus River Cave, then 20 hours later to Elmvale springs. It is likely, though unproven, that the intermittent stream

in the Fergus River Cave is a part of this flow. Elmvale functions as the local base level, draining the south-central Burren and a proportion of the water sinking at An Clab.

3. The catchment for the Carran depression drainage is probably not significantly greater that the topographic basin itself. Groundwater drainage to the south and south-southwest is initially down dip and shallow in character, but there is also groundwater flow to the north via conduits extending much deeper along veins which penetrate the otherwise impermeable wayboards. Thus, there are two vertically stacked, and in places overlapping, groundwater systems operating in the area; a superficial, down-dip system flowing southwards overlying a deep, north flowing system.

Of the mean annual recharge to the Carran enclosed depression (estimated at 10 x 10^6 m^3), c. 15% is known to flow south to the River Fergus, while c. 30% flows north via Poll Gonzo to the marine springs in Galway Bay offshore from Bellharbour/Aughinish. This requires a catchment for Poll Gonzo, within the Carran depression c.2.6km^2, although, neither the location nor character of this internal catchment is apparent.

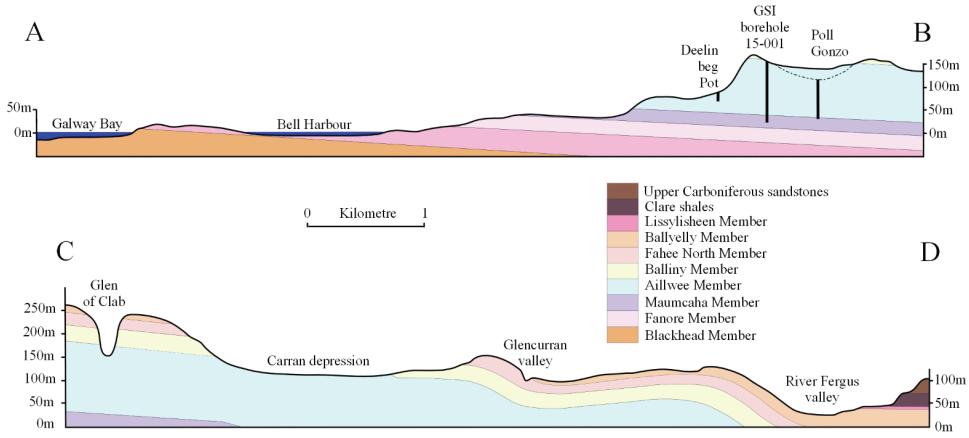

Figure 10. *Geological cross sections; showing the geological structure to the north of Carran (A-B) and to the south of Carran (C-D). Location lines shown on Figure 1. (Greatly exxagerated vertical scale.)*

4. From the above it appears that the catchment boundaries between groundwater flowing north to Galway Bay and south to the River Fergus (and the Shannon estuary) shown in Drew (1988) are incorrect and that the area draining to the River Fergus should be reduced by c. 20 km^2 and that draining to Ballyvaughan springs by c. 6km^2. This increases the size of the Bellharbour catchment by c. 26km^2 (65%).

5. Sweeting (1953) remarked that: [the Carran depression] "is entirely enclosed, its drainage having no surface outlets; it is, moreover, subjected to periodical flooding and is the best example of what is probably a true polje in the British isles". This term has been used in derivative literature ever since, although with no additional supporting evidence.

Poljes (the name relates to the Dinaric karst and other terms are used elsewhere) are associated with karsts of Mediterranean and tropical areas rather than temperate climates and so the Carran feature is untypical of temperate karsts. Gams (1978) suggests that a polje must fulfil the following criteria:

- Be a closed basin with relatively steep marginal slopes.
- Possess a relatively flat floor, with or without sediments.
- Have karstic drainage.
- Have a minimum width of 400 m.

Carran fulfils all of these criteria and with a floor area of c.8km2 and an elongate form, is 'typical' of most of the world's reported poljes. In addition, many poljes have seasonal lakes and contain numerous sub-drainage basins; Carran shares both of these characteristics.

It is less easy to fit Carran into a genetic classification of poljes, for example, the three categories of polje proposed by Ford and Williams (2007):

- *Border poljes*: where karstic and non-karstic rocks are juxtaposed. The Carran feature does not conform to this scenario though it may have done so in the past when the overlying Namurian strata extended further to the east than at present.
- *Structural poljes*: associated with fault determined depressions and/or inliers of non-limestone strata. The Carran depression shows little structural control other than perhaps in terms of the orientation of the more southerly limb which is parallel to the fold axis trend and the influence of the siliceous veins on the northwestern limb.
- *Base level poljes*: which are windows into the water table. In the case of Carran the water table is >70m below the basin floor. However, there is a perched, seasonal water table in the depression created by the restricted capacity of the drainage routes out of the turlough and this has presumably favoured lateral solution of the depression slopes.

It may be appropriate to regard the Carran depression as a small polje the development of which has been strongly controlled by the presence of the clay wayboards in the upper part of the Burren Formation limestones. The impermeable clay has functioned as an inlier of non-limestone rock and has caused a perched water table (with periodic flooding) to be maintained. The Carran polje thus has elements of both a structural and a base-level polje as defined by Ford and Williams.

6. The investigations detailed in this paper have clarified some aspects of the hydro-geomorphology of the Carran polje and adjacent areas, but significant questions remain unresolved. For example:

- The destination of only c. 45% of groundwater recharge in the Carran polje is known. The recharge mechanism and flow routes for the remaining 55% are unclear. It may be that much of the water flows north via as yet undiscovered cave systems similar to Poll Gonzo. However, any such caves may be difficult to locate as there was no expression of the Poll Gonzo vein system at the surface.
- The mechanism by which the Carran and adjacent enclosed depressions developed is speculative at present, as is the time-scale involved.

- Equally, the relationship between the Glencurran valley and cave, the Fergus River Cave and the Carran polje is unknown.
- The north-eastern limb of the Carran polje (sub-basin E) remains un-investigated despite the presence, under wet conditions, of large springs and of significant landforms (the Glen of Clab and Poulavallan).
- The lack of significant deposits of Quaternary and/or earlier deposits is puzzling given the apparently considerable age of the landform.

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